ASME B89.7.5-2006

(Technical Report)

Metrological Traceability of Dimensional Measurements to the SI Unit of Length

The American Society of Mechanical Engineers

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Date of Issuance: July 17, 2006

This Technical Report will be revised when the Society approves the issuance of a new edition. There will be no addenda issued to this edition.

The American Society of Mechanical Engineers
Three Park Avenue, New York, NY 10016-5990

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FOREWORD

The ISO Guide to the Expression of Uncertainty in Measurement (GUM) is now the internationally accepted method to express measurement uncertainty [1]. The U.S. has adopted the GUM as a national standard [2]. The evaluation of measurement uncertainty has been applied for some time at national measurement institutes, but more recently, issues such as measurement traceability and laboratory accreditation are resulting in its widespread use in calibration laboratories.

Given the potential impact on business practices, national and international standards committees are working to publish new standards and technical reports that will facilitate the integration of the GUM approach and consideration of measurement uncertainty. In support of this effort, ASME B89 Committee on Dimensional Metrology has formed Division 7: Measurement Uncertainty.

Measurement uncertainty has important economic consequences for calibration and measurement activities. In calibration reports, the magnitude of the uncertainty is often taken as an indication of the laboratory quality, and smaller uncertainty values generally are of higher value and cost. ASME B89.7.3.1, Guidelines for Decision Rules: Determining Conformance to Specifications [3], addresses the role of measurement uncertainty when accepting or rejecting products based on a measurement result and product specification. ASME B89.7.3.2, Guidelines for the Evaluation of Dimensional Measurement Uncertainty [4], provides a simplified approach (relative to the GUM) to the evaluation of dimensional measurement uncertainty. ASME B89.7.3.3, Guidelines For Assessing the Reliability of Dimensional Measurement Uncertainty Statements [5], examines how to resolve disagreements over the magnitude of the measurement uncertainty statement. Finally, ASME B89.7.4.1, Measurement Uncertainty And Conformance Testing: Risk Analysis [6], provides guidance on the risks involved in any product acceptance/rejection decision.

Historically, measurement traceability was an effort to ensure accuracy through paperwork; the requirement to show calibration reports forced instruments and standards to be calibrated. The International Vocabulary of Basic and General Terms in Metrology (VIM) [7] definition of traceability now requires a GUM-compliant uncertainty statement that provides a quantitative accuracy statement of the measurement result, a significant improvement over a calibration report number.

The VIM definition does not specify the requirements regarding the “stated references,” i.e., measurement standards, or what constitutes an appropriate terminus for the “unbroken chain of comparisons.” In a standard on “General requirements for the competence of testing and calibration laboratories,” ISO 17025 [8] states (in para. 5.6.2.1.1), “A calibration certificate bearing an accreditation body logo from a calibration laboratory accredited to this International Standard, for the calibration concerned, is sufficient evidence of traceability for the calibration data reported.” In this report, the concept of traceability developed in ISO 17025 is used as the basis to extend beyond calibration laboratories and into the industrial metrology domain.

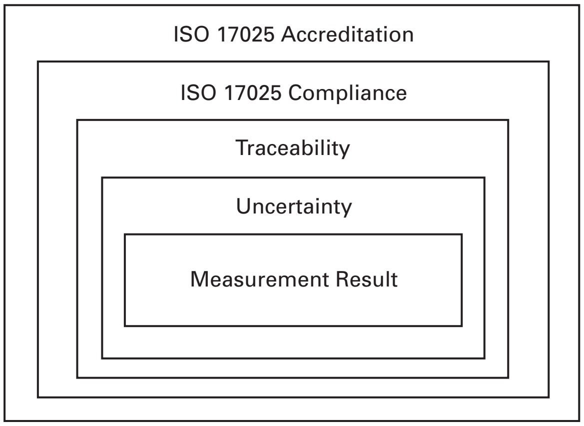
The ambiguity in the VIM definition of what constitutes a reference standard and what constitutes an unbroken chain of comparisons leads to multiple interpretations. Some practitioners believe that the only appropriate terminus for a reference standard must be a national or international standard. Others believe any calibration certificate will suffice. Similarly, which uncertainty components must have “an unbroken chain of comparisons” is also unclear, e.g., dimensional measurements often involve numerous influence quantities, such as temperature, force, physical constants, or any of a large number of other parameters that appear in the uncertainty budget. Such a chain could easily be very complex.

More fundamentally, the entire concept of an unbroken chain is blurred when uncertainty is evaluated using the GUM. The GUM permits Type B evaluations, which are based on “expert judgment,” and these terminate not at the SI unit but in the mind of the “expert.” In the measurement of large workpieces, the uncertainty of the thermal expansion coefficient can be the single largest component of the uncertainty budget, and the value of the expansion coefficient together with its uncertainty is almost always guessed. Since a GUM uncertainty evaluation can allow the largest contributor to the measurement uncertainty to have documentary traceability only to the mind of the expert, providing extensive paperwork documenting the calibration history of other subsidiary influence quantities involved in the measurement is of limited value.

Upon reviewing beliefs regarding the intent of metrological traceability, it is clear the concept must span a wide variety of applications, from the highest level calibration laboratories to shop floor measurements of production workpieces. Furthermore, any requirements must be economically practical and not generate substantial paperwork that adds little value to the measurement result. Accordingly, while ASME B89.7.5 requires the assessment of all significant uncertainty sources in the uncertainty statement, the additional requirement that the principal length standard(s) must have documentation traceability describing their connection to an appropriate metrological terminus seems to be a reasonable compromise.

Different practitioners have different needs regarding measurement documentation. In many cases, only the measurement value is needed. Other times, the measurement uncertainty is also required, e.g., to show that the measurement is "capable" for the task, some practitioners want to assert metrological traceability for contractual reasons, others want to claim ISO 17025 compliance, while still others need to assert that the measurement result is from an ISO 17025-accredited facility.

The relationship of various quality assurance topics is shown in the diagram below (each level requires all those requirements nested within it). Measurement uncertainty is a necessary but not sufficient condition for metrological traceability, as metrological traceability also requires information about the "unbroken chain back to stated references." Metrological traceability is a necessary but not sufficient condition for ISO 17025 compliance, as ISO 17025 also requires a documented quality system. ISO 17025 compliance is a necessary but not sufficient condition for ISO 17025 accreditation, as accreditation also requires external audits.



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METROLOGICAL TRACEABILITY OF DIMENSIONAL MEASUREMENTS TO THE SI UNIT OF LENGTH

ABSTRACT

The purpose of this report is to provide guidelines for demonstrating the traceability of dimensional measurements to the SI unit of length (the meter). The International Vocabulary of Basic and General Terms in Metrology (VIM) [7] provides a general definition of traceability. However, many details are not specified by this definition. This report provides an interpretation of the VIM definition.

The demonstration of metrological traceability of a dimensional measurement per B89.7.5 requires the following:

(a) clear statement of the measurand (the quantity under measurement)

(b) identification of the measurement system and/or standards used in the measurement

(c) a statement of the measurement uncertainty for the measurement result, consistent with the principles described in the Guide to the Expression of Uncertainty in Measurement [1, 2]

(d) an uncertainty budget that describes and quantifies the significant uncertainty contributors

(e) documentation traceability of the length standard(s) used in the measurement back to an appropriate metrological terminus

(f) a measurement assurance program that assures that the measurement system (and other standards if used) and the conditions of the measurement are within the validity conditions of the measurement uncertainty statement

1 INTRODUCTION

This report describes the requirements for a particular interpretation[1] of metrological traceability[2] to the SI unit of length, i.e., the meter, for dimensional measurements, consistent with the definition in The International Vocabulary of Basic and General Terms in Metrology (VIM) [7]. The purpose is to provide a functional and usable interpretation that allows producers and customers of dimensional measurement results to agree on how to establish and demonstrate metrological traceability. A benefit of this report is that it clarifies and specifies many issues that are often debated when discussing traceability and allows the reader to understand the complexity of the traceability topic.

The VIM defines measurement traceability as

(Metrological) Traceability (VIM 1993 definition 6.10) : property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties.

Historically, the principal driver for demonstrated traceability in the U.S. had been military specifications intended to ensure the quality of measurements associated with equipment procurement. Traceability was primarily a paper trail of calibration report numbers leading back to a National Measurement Institute (NMI), e.g., the National Institute of Standards and Technology (NIST). Today, metrological traceability is still tied to efforts to ensure measurement quality but (using the VIM definition) has a quantitative aspect involving measurement uncertainty. The Guide to the Expression of Uncertainty in Measurement (GUM) [1, 2] provides a unified method to evaluate measurement uncertainty that represents a quantitative measure of the quality of a measurement result. Indeed, a GUM-compliant uncertainty statement must have all significant sources of uncertainty evaluated; hence, the length standard (from which the unit of length enters the measurement) must also have its uncertainty quantitatively evaluated. This implicitly means that there must be some connection back to the SI unit, as otherwise, such a quantitative evaluation could not be performed.

From the perspective of measurement uncertainty, it is clear that traceability does not require the use of an identical type of artifact for comparison during a calibration. Rather, it is a chain of information connected at one end to the SI unit and the other end to the artifact

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[1] The requirements described in this report are an interpretation of the 1993 VIM definition of traceability by the ASME B89.7.5 committee; practitioners who seek to invoke this interpretation should cite "metrological traceability per B89.7.5." Other organizations may have other interpretations of traceability.

[2] In this report, the qualifier "metrological" preceding the term "traceability" is used to distinguish this concept of traceability (the property of the result of a measurement) from other uses of the same word, such as being able to trace the history, application, or location of supplied products, parts, or materials.

or instrument under calibration or inspection. The quality of the chain is stated quantitatively by means of a GUM-compliant uncertainty statement.

Most NMIs and high-accuracy calibration laboratories satisfy their traceability needs through compliance with, or accreditation to, such standards as ISO 17025 [8] or ANSI/NCSL Z540-1 [9]. These standards exceed the scope of B89.7.5 and include many additional requirements, such as an extensive quality plan and external measurement audits. ASME B89.7.5 seeks to address a broader range of dimensional metrology practitioners, including those performing measurements on the factory floor, who occasionally need to show metrological traceability for their measurement results. This report examines some of the current issues with the metrological traceability concept and provides guidelines for demonstrating metrological traceability according to the B89.7.5 interpretation.

2 REQUIREMENTS FOR METROLOGICAL TRACEABILITY OF DIMENSIONAL MEASUREMENTS

(a) The demonstration of metrological traceability of a dimensional measurement per B89.7.5 requires

(1) clear statement of the measurand (the quantity under measurement)

(2) identification of the measurement system and/or standards used in the measurement

(3) statement of the measurement uncertainty for the measurement result, consistent with the principles[3] described in the GUM

(4) an uncertainty budget that describes and quantifies the significant uncertainty contributors[4]

(5) documentation traceability[5] of the length standard(s) used in the measurement back to an appropriate metrological terminus

(6) measurement assurance program[6] that ensures the measurement system (and other standards if used) and conditions of the measurement are within the validity conditions of the measurement uncertainty statement

(b) The length standard(s) used in a dimensional measurement introduces the unit of length into the measurement result. It is recognized that there are many influence quantities[7] that affect a measurement result and that the length standard(s) may not be the largest contributor to the uncertainty associated with the result. Typically, there are only a few length standards used in a measurement, e.g., when calibrating a caliper by measuring gage blocks, the gage blocks are the length standards that require documentation to an appropriate terminus. In a unidirectional length measurement using a laser interferometer, the vacuum wavelength of the laser is the length standard. If the laser interferometer length measurement were bidirectional, i.e., measuring a feature of size such as the width of a slot, then a second length standard may also be employed to evaluate the effective probe size [in a Coordinate Measuring Machine (CMM), this is usually the calibration sphere used to set the stylus tip size; in a laser tracker, this is the standard used to evaluate the size of the retroreflector].

(c) An appropriate metrological terminus for the documentation traceability of the length standard(s) is one of the following:

(1) a calibration report[8] from an NMI for the length standard(s) used in the measurement.

(2) a calibration report[8] from a competent[9] laboratory fulfilling Section 5.6 of ISO 17025 or Section 9 of ANSI/NCSL Z540-1 for the length standard(s) used in the measurement.

(3) documentation describing the means of realizing of the SI meter[10] used as the unit of length transferred to (or used as) the length standard(s). This documentation will include the uncertainty of the realization of the meter and evidence that the stated uncertainty has been achieved. This evidence will include measurement of independently calibrated artifact(s) having an uncertainty no greater than that claimed and with documentation traceability either directly or indirectly to an NMI [i.e., using either metrological terminus path (a) or (b) above], and that the measurement error (the difference

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[3] The details of the measurement uncertainty statement are determined by the nature of the measurement; calibration laboratory results will typically be much more detailed than lower accuracy industrial measurements.

[4] In the case where the uncertainty is evaluated using Monte Carlo computer simulation, a description of the software and the values of the input quantities are sufficient.

[5] In this report, a distinction is made between metrological and documentation traceability. Documentation traceability is the ability to provide documentary evidence, e.g., calibration reports, required in a traceability chain.

[6] The quality assurance program may be simple or complex but must be sufficient to ensure that the measurement uncertainty statement is valid. Typically, this involves monitoring the status of the measurement system (and other standards if used) and the conditions of measurement.

[7] The phrase "influence quantity" is defined by the GUM as a quantity that is not the measurand but that affects the result of the measurement.

[8] For some instruments, e.g., machinist scales or calipers, accuracy is often specified by grade or class. A document identifying compliance to a metrological grade or class is equivalent to a calibration report.

[9] A de facto means of demonstrating laboratory competence is through laboratory accreditation.

[10] In this report, a realization of the meter is considered a reproducible physical phenomenon that has its metrological characteristic (and reproducibility) measured and documented by an NMI, e.g., the vacuum wavelength of certain spectral lamps. Hence, reproduction of this phenomenon represents an unbroken chain of information, back to the SI unit of length. The realization of an SI unit is sometimes referred to as an intrinsic standard or a quantum-based standard.

between the measured value and independently calibrated value) is less than the Root-Sum-of-Squares (RSS) value of the two expanded uncertainties, e.g., the documentation could be a document showing participation in a round robin where the measurand has a calibrated value having an appropriate metrological terminus and the measurement error is less than the RSS value of the two expanded uncertainties. Another example could be a document showing a comparison against another independently calibrated length standard having an appropriate metrological terminus and a measurement error less than the RSS value of the two expanded uncertainties.

3 DETAILS OF DIMENSIONAL METROLOGICAL TRACEABILITY

(a) Metrological traceability is always to the SI unit, but an appropriate metrological terminus for the traceability documentation can be an NMI, a competent laboratory fulfilling the traceability sections of ISO 17025 and NCSL Z540-1, or a realization of the SI meter.

(b) Organizations are not traceable; only the results of their measurements can be.

(c) Metrological traceability is an attribute of a measurement result. In some situations, an instrument is calibrated for a specific measurand with a measurement uncertainty statement having extended validity conditions, i.e., the uncertainty statement is valid over a range of values for some influence quantities [10]. In this case, the measurement results of the instrument are metrologically traceable whenever the measurement conditions are within the (extended) validity conditions of the uncertainty statement. Sometimes this is referred to informally as a traceable instrument, meaning that all measurement results of the instrument are metrologically traceable provided the measurement conditions fulfill the metrological requirements described in the validity conditions of the uncertainty statement.

(d) Metrological traceability does not imply any particular level of accuracy. A measurement made with a scale graduated in millimeters and a second measurement made with a micrometer graduated in micrometers can both produce traceable measurements, albeit with very different stated uncertainties.

(e) Competent laboratories are acceptable metrological termini provided the measurement of the length standard is within their scope of capabilities.

(f) Since metrological traceability requires a valid statement of measurement uncertainty, any information or condition that invalidates the uncertainty statement, e.g., wear or drift, also invalidates the metrological traceability.

(g) Metrological traceability to a specific NMI, e.g., to NIST, requires evidence that the documentation traceability chain terminus is that specific NMI. The phrase "traceability to an NMI" is interpreted to mean metrological traceability of a measurement result that has documentation traceability back to a metrological terminus provided by that NMI. If intermediate laboratories are involved in the traceability chain, including accredited laboratories, their documentation traceability must state that it terminates at that specific NMI.

(h) In some standards, the term "traceability" has a different meaning depending upon the context. ISO 9000 [11] uses the definition shown below, with the noted exception that the VIM definition is to be used in the field of metrology.

Traceability (ISO 9000: 2000): ability to trace the history, application, or location of that which is under consideration.

NOTE: In the field of metrology, the definition in VIM:1993, 6.10, is the accepted definition.

Both the ISO 9000 and VIM definitions may exist in the same organization, e.g., an ISO 9000-certified site might also be ISO 17025 accredited.

4 EXAMPLES OF DEMONSTRATING METROLOGICAL TRACEABILITY

4.1 Factory Floor Workpiece Measurements Using a Caliper

A factory making components under contract to another organization is required to have all measurements of a particular set of components traceable per B89.7.5. The factory has 100-mm steel calipers, having a coefficient of thermal expansion (CTE) of $(11.5 \pm 1) \times 10^{-6}/°\text{C}$ in use, measuring workpieces with a CTE ranging from invar ($1 \times 10^{-6}/°\text{C}$) to aluminum alloys ($22 \times 10^{-6}/°\text{C}$) in a thermal environment varying from 15°C to 25°C. The calipers have a resolution of 10 μm and a calibration certificate stating that the maximum permissible error (MPE) is less than 10 μm over the full range when measuring at 20°C. The following satisfies the B89.7.5 requirements for all calipers. The workpiece and caliper are assumed to be within 0.2°C of each other during a measurement.

(a) Measurand. A two-point, bidirectional length of a rigid engineering material with a CTE between $1.0 \times 10^{-6}/°\text{C}$ and $23 \times 10^{-6}/°\text{C}$, measured by a caliper.

(b) Measurement System. A 100-mm digital caliper, company ABC, model XYZ, calibrated by a Z540-1-accredited laboratory; each caliper bears a sticker showing it passed the calibration having an MPE less than 10 μm over its full range when measuring at 20°C.

(c) Uncertainty Statement. The expanded uncertainty is U (k = 2) = 16.4 μm; valid for measurements of workpieces up to 100 mm in length, made of common metallic engineering materials with a CTE between $1 \times 10^{-6}/°\text{C}$ and $22 \times 10^{-6}/°\text{C}$, measured within a temperature range of 15°C to 25°C.

(d) Uncertainty Budget[11]

(1) Resolution of the Caliber. Using a Type B evaluation with a uniform distribution yields a standard uncertainty of 2.9 μm.

(2) Calibration report at 20°C states that maximum error is less than 10 μm over entire caliper travel; assigning a Type B uniform distribution yields a standard uncertainty of 5.8 μm.

(3) Differential Thermal Expansion. The caliper is assumed to have a thermal expansion coefficient of $(11.5 \pm 1) \times 10^{-6}/°\text{C}$, implying a maximum uncorrected CTE of $11.5 \times 10^{-6}/°\text{C}$ yielding a maximum error (at $L = 100$ mm and $T - 20°\text{C} = 5°\text{C}$) of 5.8 μm, assuming a Type B triangular distribution for the errors, yields a standard uncertainty of 2.3 μm.

(4) The maximum error due to a possible temperature difference between the workpiece and caliper is evaluated by computing the maximum error found from using the maximum measured length $L = 100$ mm, the maximum value of the caliper CTE is $12.5 \times 10^{-6}/°\text{C}$, and the maximum temperature difference between the caliper and workpiece, which is 0.2°C, yielding a maximum error due is 0.25 μm. Assigning a Type B triangular distribution to this possible error gives a standard uncertainty of 0.1 μm.

(5) Anvil flatness and parallelism effects are evaluated using a small gage wire measured in multiple positions and orientations. Variation of the results leads to the assignment of a Type A standard uncertainty equal to 4.5 μm.

(6) Combined standard uncertainty $u_c = \sqrt{2.9^2 + 5.8^2 + 2.3^2 + 0.1^2 + 4.5^2}\ \mu\text{m} = 8.2\ \mu\text{m}$.

(7) The expanded uncertainty is $U\ (k = 2) = 2 \times 8.2\ \mu\text{m} = 16.4\ \mu\text{m}$.

(e) Documentation Traceability. Satisfied by a calibration report from the Z540-1-accredited laboratory showing that all calipers had a maximum error less than 10 μm at 20°C.

(f) Company quality assurance policy requires training on the proper use of calipers, that calipers are calibrated once per year or after possible damage, and ensures that measurements are performed only within the 15°C to 25°C environment.

NOTE: If a smaller expanded uncertainty is required, then a separate uncertainty statement can be produced by restricting the thermal environment, length of the workpiece, or the workpiece CTE.

4.2 Workpiece Measurements by a CMM

An important workpiece has 15 critical features that require traceability per B89.7.5. The stainless steel workpiece is measured on a CMM that has been calibrated per B89.4.1 by an ISO 17025-accredited laboratory. The CMM is in a thermal environment compliant with the B89.4.1 specifications.

(a) Measurand. The critical features are identified on the blueprint by their geometric dimensioning and tolerancing (GD&T) callouts that include feature size, position, form, and orientation; the workpiece is made of stainless steel.

(b) Measurement System. A CMM, model XYZ, using probe type ABC with stylus configuration IJK; the CMM is calibrated by an ISO 17025-accredited laboratory per B89.4.1.

(c-d) Uncertainty Statement and Budget.[12] Due to the number of features and the complexity of the measurement system, a Monte Carlo simulation method is selected to produce the uncertainty statement. The metrologist lists the influence quantities, such as CMM geometrical errors, CMM thermal errors, CMM probing errors, measurement point sampling strategy, workpiece thermal errors, workpiece feature form errors, etc. The metrologist then ensures that each influence quantity is accounted for in some input of the Monte Carlo simulation software. In this example, we will assume this is true; if some influence quantities were not accounted for in the simulation software, then their effect on the uncertainty of the measurements would need to be separately evaluated and then combined with the simulation results. The simulation produces an expanded uncertainty statement for each of the critical features and a report documenting all of the input parameters used in the simulation and requiring the thermal environment to be compliant with the B89.4.1 specifications.

(e) Documentation Traceability. Satisfied by a report from the ISO 17025-accredited laboratory that calibrated the CMM.

(f) Company quality assurance policy requires that the CMM operator is properly trained and the CMM undergoes regular interim testing (see B89.4.1 Appendix I). The policy also ensures that the measurements are conducted within the assumed thermal environment and use the equipment (probes, styli, etc.), specified in the uncertainty report.

4.3 Laser Interferometery Length Measurement

A laboratory measures the distance between two kinematic seats on a gage and needs traceability per B89.7.5. The temperature is 22°C, and the nominal thermal expansion is computed and measurement result correspondingly adjusted. The distance is measured using a displacement-measuring laser interferometer and a spherically mounted retroreflector (SMR); the laser is cited as realization of the SI meter.

(a) Measurand. The point-to-point length between two kinematic seats on a steel gage.

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[11] This example is taken from ASME B89.7.3.2. See this Standard for details of the evaluation of the measurement uncertainty.

[12] In this example, the uncertainty statement and budget steps are combined as both depend on the simulation output.

(b) Measurement System. A displacement laser interferometer and SMR, model number XYZ serial number 123.

(c) Uncertainty Statement. The expanded uncertainty for the distance between the two points at the center of an SMR located by kinematic seats on the gage is 2.8 μm + $4.0 \times 10^{-6} \times L$, where L is in meters. It is valid at a temperature of 20°C with the gage supported directly under each kinematic seat.

(d) Uncertainty Budget

(1) Vacuum Wavelength. Standard uncertainty: $1 \times 10^{-6} \times L$.

(2) Index of Refraction Correction. Standard uncertainty: $1 \times 10^{-6} \times L$.

(3) Uncertainty in the gage CTE is $\pm 1 \times 10^{-6}/°C$, using a Type B uniform distribution yields a standard uncertainty of $0.58/°C \times L \times 2°C = 1.2 \times 10^{-6} \times L$.

(4) Uncertainty in the gage temperature measurement is ±0.1°C using a Type B uniform distribution yields a standard uncertainty of $0.058°C \times L \times 11.5 \times 10^{-6}/°C = 0.66 \times 10^{-6} \times L$.

(5) Repeatability of locating the SMR in a kinematic nest is 1 μm assessed by a Type A evaluation; since there are two nests and the repeatability appears random, this yields a standard uncertainty of 1.41×1.0 μm = 1.4 μm.

(6) Resolution and alignment errors are negligible.

(7) Combined standard uncertainty: 1.4 μm + $2.0 \times 10^{-6} \times L$.

(8) Expanded ($k = 2$) uncertainty: 2.8 μm + $4.0 \times 10^{-6} \times L$.

(e) Documentation Traceability. The laboratory cites the laser as realization of the SI meter. The laboratory has participated in a recent laboratory intercomparison measuring the point-to-point length using the laser interferometer with an SMR. The pilot lab for the round robin is ISO 17025 accredited for this measurement and stated the uncertainty of the artifact to be 2.5 μm + $3.0 \times 10^{-6} \times L$. The results of the intercomparison show that the laboratory's measurement error was less than the RSS of the two uncertainties.

(f) Company's quality assurance policy specifies periodic laboratory intercomparisons, details of the laser alignment procedure, and periodic calibration of the weather station used in the index of refraction calculation.

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ASME B89.7.5-2006

ISBN 0-7918-3011-X

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L08406